# THE STABILITY OF FLAME HOLDERS

by

James B. Osborn, Lt. Commander,
United States Navy

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JAMES B. OSBORN, LIEUTENANT COMMANDER,

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# THE STABILITY OF FLAME HOLDERS

## INTRODUCTION

A flame holder is a device placed in a stream of rapidly flowing combustible mixture to anchor the flame and to make burning possible. The flame holder has its most immediate application in the ram jet field, where counter flows are impractical, and it is desirable that combustion take place at as high a stream velocity as possible. The desired stream velocities far exceed the flame propagation velocities; thus, the flame holder is introduced into the stream to prevent the blowing out of the flame from the combustion region and to anchor the flame at a predetermined point.

To date no satisfactory theory exists in the published literature as to the mechanism by which the flame holder accomplishes its mission, and most of the progress that has been made thus far has been made by trial experiment in the laboratory. There is, however, one detail in which all flame holders, no matter how complicated they may appear, are similar. They have built into them an exit area to approach area ratio.

The purpose of this paper is to attack the problem of flame holder stability as a flow problem from an area ratio point of view in an effort to establish the stable region of operation for a flame holder. This field of stable operation derived on a flow basis will be valid only as long as the requisites for combustion are met.

Most of the studies in burning streams have been made on flame propagation.(1)* The main purpose is to relate the velocity of the flame front relative to the unburnt gas to the fundamental physical and chemical properties of the combustible mixture. Although the first attempts to solve this problem were made as long ago as fifty years, the problem is still not solved, and what has been accomplished is of little value as far as practical application is concerned.

The main reason for the failure of solution of the flame propagation problem became apparent when research of combustion reactions revealed the extremely complicated nature of the ordinary combustion process. It is now common knowledge to those working in the field of combustion reaearch that combustion reactions take place by long, complicated reaction chains involving unstable intermediate products.(2)* Complete knowledge of the details of these reaction chains has not yet been compiled, but the basis of the theory appears very sound and has been completely worked out for some of the simpler reactions. The present chemical

representation of combustion equations merely represents a hypothetical combustion mechanism. These equations indicate the initial and end products, but they do not reveal the complicated path of the actual combustion process which controls the rate of energy release from the fuel and, consequently, the efficiency of burning.

To include the effects of heat conduction, diffusion, and chemical kinetics, modified by complicated flow conditions in a theory for flame holders, is completely out of the question at the present time both from the mathematical complication involved and the fact that the details of the chemical kinetics are not fully understood. The idea of this paper is to treat the combustion process in a flame holder as a flow phenomena, with the complicated mechanism of combustion present at all times, in an attempt to predict the region of stable operation of a flame holder of given area ratio.

## THEORETICAL DEVELOPMENT

As stated before, the objective of the investigation was to find a basis for which the temperature range of stable operation could be estimated from the area ratio of a flame holder. Although it has been previously pointed out that the mechanism of combustion is very complicated, in the following development the mechanism is assumed to exist.

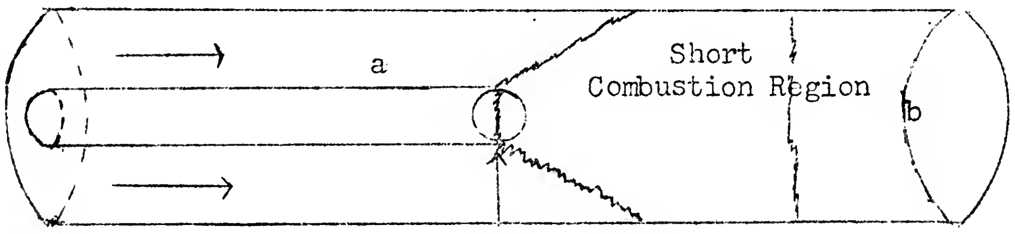



Figure A

Assumptions:

1. Short combustion region with negligible capacity to store gases.
2. Flow at approach to flame holder, state (a), is pressure sensitive only.
3. Flow at the exit of the combustion region, state (b), is both temperature and pressure sensitive.
4. The combustion process, stabilized by the flame holder is independent of flow conditions and is present at all times.

Expressing the assumptions mathematically we have,

From assumption 1: $W_a = W_b$ . . . . . . . . . . . . . . (1)

From assumption 2: $W_a = f\ (P)$ . . . . . . . . . . . . . (2)

From assumption 3: $W_b = f\ (P, T)$ . . . . . . . . . . . (3)

Differentiating (2) and (3):

$$dW_a = \frac{dW_a}{dP}\ dP \qquad (4)$$

$$dW_b = \frac{\delta W_b}{\delta P}\ dP + \frac{\delta W_b}{\delta T}\ dT \qquad (5)$$

If we expand to finite increments about some stable point of operation, state o, defined by $W_o$, $P_o$, and $T_o$, equations (3) and (4) become,

$$W_a - W_o = \frac{dW_a}{dP}\ (P - P_o) \qquad (6)$$

$$W_b - W_o = \frac{\delta W_b}{\delta P}\ (P - P_o) + \frac{\delta W_b}{\delta T}\ (T - T_o) \qquad (7)$$

If fuel remains constant considering constant specific heats,

$$W_o\ (T_o - T_a) = W_a\ (T - T_a), \text{ or}$$

$$T = T_a + \frac{W_o}{W_a}\ (T_o - T_a) \qquad (8)$$

Subtracting $T_o$ from both sides of equation (8),

$$T - T_o = -(T_o - T_a)\ \left(1 - \frac{W_o}{W_a}\right) = -\ \frac{(W_a - W_o)\ (T_o - T_a)}{W_a}$$

But $\frac{W_a - W_o}{W_a} \approx \frac{W_a - W_o}{W_o}$

$$T - T_o \approx -(T_o - T_a) \frac{(W_a - W_o)}{W_o} \quad \ldots\ldots\ldots\ldots (9)$$

Substituting (9) in (7),

$$W_b - W_o = \frac{\delta W_b}{\delta P} (P - P_o) - \frac{\delta W_b}{\delta T} \frac{(W_a - W_o)}{W_o} (T_o - T_a) \quad \ldots (10)$$

But from (6) $W_a - W_o = \frac{dW_a}{dP} (P - P_o)$

Substituting (6) in (10),

$$W_b - W_o = \frac{\delta W_b}{\delta P} (P - P_o) - \frac{\delta W_b}{\delta T} \frac{dW_a}{dP} (P - P_o) \frac{(T_o - T_a)}{W_o}$$

or,

$$\frac{W_b - W_o}{P - P_o} = \frac{\delta W_b}{\delta P} - \frac{(T_o - T_a)}{W_o} \frac{\delta W_b}{\delta T} \frac{dW_a}{dP} \quad \ldots\ldots (11)$$

The moment there is a pressure disturbance in the combustion region, a velocity is propagated counter flow due to the pressure disturbance.(4)* The effect can be expressed mathematically as follows:

$$dP = - dV \sqrt{E \rho} \qquad \text{Where } E \text{ is bulk modulus} \quad E = \gamma P_o$$

or,

$$dV = - \frac{(P - P_o)}{\sqrt{E \rho}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

But $\quad W = \rho A V g$

Assuming constant density,

$$dW_a = \rho Ag\ dV = -\rho Ag \frac{(P - P_o)}{\sqrt{\gamma P_o \rho}}$$

But

$$P_o\ P_a // P_a^2 \quad \text{and} \quad \frac{W_a - W_o}{P - P_o} // \frac{dW_a}{dP}$$

$$\frac{W_a - W_o}{P - P_o} // \frac{dW_a}{dP} // - Ag \sqrt{\frac{T_a}{\gamma g R} \frac{1}{T_a}}$$

or,

$$\frac{P_o dW_a}{W_o\ dP} = \frac{-\sqrt{\frac{g}{\gamma R}}}{\frac{W_o}{A_a} \frac{\sqrt{T_a}}{P_o}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Similarly, the pressure disturbance causes a velocity to be propagated with the flow.

$$dWb = \rho_2\ Ag\ dV$$

Where $dV = \frac{(P - P_o)}{\sqrt{EP_o}}$ Where E is bulk modulus $E = \gamma P_o$

Analogous to the derivation for counter flow disturbance,

$$\frac{P_o}{W_o} \frac{dWb}{dP} = \frac{\sqrt{\frac{g}{\gamma R}}}{\frac{W_o}{Ab} \frac{\sqrt{T_o}}{P_o}} \quad \ldots\ldots\ldots\ldots\ldots (14)$$

Since,

$$W = \rho AgV = \frac{P}{RT} AV$$

Taking logarithms and differentiating,

$$\frac{\delta W}{W} = -\frac{\delta T}{T} \quad \text{or} \quad \frac{T}{W}\,\frac{\delta W}{\delta T} = -1$$

But,

$$\frac{T}{W}\,\frac{\delta W}{\delta T} = -1 + \frac{T_o}{W_o}\,\frac{\delta Wb}{\delta T} \qquad \ldots\ldots\ldots\ldots\ (15)$$

Multiplying and dividing (11) by $\frac{W_o}{P_o}$, and supplying in the second term on the right a $\frac{T_o}{T_o}$, we have,

$$\frac{Wb - W_o}{P - P_o} = \left[\frac{P_o}{W_o}\,\frac{dWb}{dP} - \frac{(T_o - T_a)}{T_o}\,\frac{T_o}{W_o}\,\frac{\delta Wb}{\delta T}\,\frac{P_o}{W_o}\,\frac{dWa}{dP}\right]\frac{W_o}{P_o}\ .\ (16)$$

Substituting (13), (14), and (15) in (16),

$$\frac{Wb - W_o}{P - P_o} = \left[\frac{\sqrt{\frac{g}{\gamma R}}}{\frac{W_o}{Ab}\,\frac{\sqrt{T_o}}{P_o}} - \frac{(T_o - T_a)}{T_o}\,\frac{\sqrt{\frac{g}{\gamma R}}}{\frac{W_o}{Aa}\,\frac{\sqrt{T_a}}{P_o}}\right]\frac{W_o}{P_o}$$

Setting $\frac{Wb - W_o}{P - P_o} = 0$ and solving for the area ratio,

$$\frac{Ab}{Aa} = \sqrt{\frac{T_o}{T_a}}\,\frac{(T_o - T_a)}{T_o} \qquad \ldots\ldots\ldots\ldots\ (17)$$

or,

$$\frac{Ab}{Aa} = \sqrt{\frac{T_o}{T_a}} - \frac{1}{\sqrt{\frac{T_o}{T_a}}} \qquad \ldots\ldots\ldots\ldots\ (18)$$

As can be seen from (18) the area ratio of a flame holder can be expressed as a function of the temperature ratio with certain simplifying assumptions and approximations.

Henceforth in this report when term area ratio of flame holder is used, it is implied the ratio of Ab/Aa or ratio of exit gas area to inlet gas area, and likewise temperature ratio is $T_o/T_a$ or ratio of exit gas temperature to inlet gas temperature.

## ANALYSIS OF PROBLEM

From the theoretical development one observes that the area ratio of a flame holder can be expressed as a function of the temperature ratio on the basis of certain approximations and assumptions. In deriving this simplified expression, the rate of change of exit weight flow from flame holder combustion region with respect to pressure in the flame holder combustion region was assumed to be zero, and the energy release of fuel was assumed to be independent of flow conditions.

A flame holder of the simplest possible construction would be built, and the area ratio of the flame holder varied by using various sizes of combustion tubes in order to verify the validity of the theoretically developed equation and to interpret its significance by experimental results.

A flame holder was constructed of standard 3/8-inch pipe with a flat plate welded over the end, the stabilizing area.

A small hole was drilled in the flat plate in order to install a pilot light for combustion initation. Various combustion tubes were mounted coaxially with the flame holder. A pre-mixed gas system was selected in order to minimize mixing and gas diffusion problems. A high pressure or stiff fuel system was selected in order that fluctuations in air supply or pulsations in burner would not be reflected into the fuel supply. With the equipment selected, by holding variations in other variables to a minimum, and varying the area ratio of flame holder by using variable combustion tubes, the importance of area ratio and temperature ratio on stability would be carried out.

The investigation was carried out in the Heat Transfer Laboratory of the Mechanical Engineering Department, Rensselaer Polytechnic Institute, Troy, New York.

# EQUIPMENT AND PROCEDURE

## EQUIPMENT

Since the objective of the experiment was to find the field of stable operation of flame holders from the standpoint of flow conditions, the simplest apparatus was selected in order to fulfill the requirements of the theoretical development. The experimental apparatus is shown schematically in Fig.(B) and (C), and in photographs 1 and 2. The essential parts of the apparatus are the air supply and air meter, the fuel supply and fuel meter, the mixing chamber, the flame holder, the pilot light, and the combustion tubes. A detailed description of each of the essential parts is as follows:

Air Supply and Air Meter: The air supply was taken from the building supply which was furnished by an Ingersoll-Rand Type 30 Compressor. The supply was held constant by opening a bleed-off valve in order to keep the compressor in continuous operation, and controlling the flow to air meter with a throttle valve. Air supply could be maintained within a .010 inch of water across the air nozzle as measured by an inclined draft gage. The air meter consisted of a standard A.S.M.E. nozzle of .488 inches in diameter made of aluminum. The nozzle was mounted in an aluminum

plate and connected by flanges to seven-inch lengths of standard three-inch pipes, the approach to and exit from the nozzle. The upstream wall tap was one-half inch from the nozzle plate and the downstream wall tap as one-eighth inch from the end of the nozzle. A Weston type dial thermometer was installed on the downstream side of the nozzle plate for measurement of air temperature. The approach and exit leads to the air meter were one-quarter inch pipes coupled to the three-inch sections. The pressure on the downstream side of the nozzle was read in inches of mercury on a standard U-tube gage, and the differential pressure across the nozzle was measured on a one-inch inclined draft gage. The nozzle coefficient of the air nozzle was assumed to be unity. It is believed that the air flow measurements were accurately determined to within two per cent.

Fuel Supply and Fuel Meter: The fuel used was propane sold under the trade name of "Pyrofax". The fuel was in liquid form with vapor pressure supplying the supply pressure. The vapor pressure of propane at $70^{\circ}$ F. is about 107 lb./sq. in. gage, which gave a more than adequate supply pressure. Some characteristics of "Pyrofax" as furnished by the

supplier are as follows:

Heating Value 21,500 BTU/lb.

Ratio of Specific Heats 1.153

A pressure reducing valve was used to control the pressure to the fuel meter. The amount of fuel used was so small that the evaporation of the fuel to a gaseous state did not lower the supply pressure which remained constant throughout the experiment. The temperature of the fuel was assumed to be that of room temperature. The reducing valve was connected to the fuel nozzle by means of rubber hose. The fuel meter consisted of a 3/8-inch pipe approach to a rounded nozzle, drilled with a number fifty drill. The exit from the nozzle was 1/4-inch standard pipe. The nozzle was made from a brass 1/4-inch pipe cap machined down to the above specifications. The approach was well rounded, but the straight section was slightly longer than that of conventional nozzles. The fuel meter was placed in series with the air meter for calibration. The details of calibration using air as the medium are shown in Appendix, Section A. The effective area was calculated to be .00425 sq. in. In order to calibrate the fuel meter with air meter as standard,

it was necessary to calibrate the fuel meter at flows far above the range at which the meter would be used, but it was decided to calibrate the meter in this way in order to have a standard that was in the system. The effective area .00425 sq. in. seems very reasonable allowing for any whip of the drill. A number sixty drill hole had also been used originally, but it was found to be too small and a larger number fifty drill hole was redrilled through it. It is considered that the fuel measurements were accurate to within five per cent.

Mixing Chamber: The mixing chamber consisted of fuel supply rod of 1/4-inch diameter stainless steel with a plugged end mounted concentrically along the axis of a 3/8-inch pipe T. The steel fuel tube was tapped by eight equally spaced number eighty drill holes, approximate diameter .0135 inches. The reason for using such small holes was to make a very stiff fuel system so that fluctuations in air supply or burner pulsations would not effect fuel supply. The fuel system did not vary with burner pulsation, but on increasing the pressure in the air system a corresponding decrease in fuel supply would be noted which would be due to the decreased pressure drop across the fuel meter.

Flame Holder: The flame holder consisted of a 3/8-inch pipe with a flat plate welded over one end. The flame holder was mounted concentrically with the combustion tubes. The same flame holder was used throughout the experiment. The diameter of the flame holder was .683 inches.

Pilot Light: In order to initiate combustion the flame holder end was tapped with a small hole. The flame holder pipe was connected to the city gas system, and a flame of one-quarter to three-eighths inches high was used for ignition. When in operation, no change in the temperature of the exit gases from the combustion tube could be detected whether the pilot light was on or off.

Combustion Tubes: The combustion tubes were two feet long and of various internal diameters. The area ratio of the flame holder was varied by using a common area flame holder and varying the internal diameter of the combustion tubes. Tubes of pyrex glass, iron and porcelain were used for temperature traverse data. Combustion tubes for the stability test were as follows:

| Composition | Internal Diameter - Inches | Area Ratio* |
|---|---|---|
| Tube 1, 50 mm pyrex | 1.828 | 1.162 |
| Tube 2, 1 1/4" iron pipe | 1.365 | 1.330 |
| Tube 3, 35 mm pyrex | 1.250 | 1.425 |
| Tube 4, 1" iron pipe | 1.055 | 1.720 |

*Based on a common flame holder area of .683 in diameter.

It was considered desirable to use some pyrex tubes accompanied by slight plasticity and slight warpage in order that the combustion region could be observed without a complicated system of mirrors.

## PROCEDURE

Pressure Measurement - All static pressures were measured on a U-tube manometer in inches of mercury. The differential pressure across the fuel meter and the air meter was measured on three- and one-inch inclined draft gage, respectively.

Flow Measurement - Section D, Appendix, outlines the method in which fuel and air flow calculations were made.

Temperature Measurement - The temperature was measured by means of a Chromel-Alumel thermocouple and a General Electric Type PJ-1-B4 Potentiometer. The conversion tables used were "Standard Conversion Tables for L. and N. Thermocouples", published by the Leeds and Northrup Company. Readings were reproducible throughout the experiment to within fifty degrees in the center of the combustion tube; however, wall readings were more erratic.

Temperature readings can be questioned on the basis of (1) long exposure at high temperatures, (2) exposure to burning in mixtures that might carburize or alter composition of thermocouple wires, (3) radiation errors. The temperature trends are of primary interest in this investigation, however. It might be pointed out that where large gradients exist in making a traverse, the readings to be observed close to the wall are the most important readings since the flow area is larger between successive radius increments. It was very difficult with the equipment available to obtain very accurate readings here where the temperature gradient was the greatest. The temperatures in proximity of the wall unfortunately are the most important in the experiment and are subject to the greatest error.

Temperature Integration - There existed in all combustion tubes a severe temperature gradient across the diameter of the tube. Since in the theoretical development only mean temperatures were used, some average temperature had to be evaluated. An impact tube was placed in the combustion tube, and the velocity traverse corresponded to the rough parabolic distribution of the temperature gradient.

Since $W = \rho AVg = \frac{PA}{R} \times \frac{V}{T}$, the static pressure across the tube was constant. If the velocity and temperature vary in the same manner across the combustion tube, then equal

areas in the tube have equal amounts of mass flux crossing them. A temperature traverse was taken across the combustion tube and plotted against the radius at various points. The combustion tube area was then divided into six equal areas and the corresponding radii were plotted in on temperature traverse plots. The temperatures of the equal area mid-points were averaged for the mean temperature. The number six was selected because a greater number of equal areas would have the effect of weighting the temperatures near the wall more; however, the temperatures near the wall are subject to the most error. Appendix, Section B, shows a compilation of the temperature traverse data calculated as outlined above. Fortunately, all the tubes tested fell close to a general temperature curve, which fitted remarkably well for all tubes at the flows tested. A general curve was plotted in which the maximum temperature, or temperature at center of tube, was plotted against the average temperature. All tubes were consistent with this curve.

Determination of Limits of Stable Burning - It was hoped that some means other than audible observation could be used to determine the stability limit. It was also suspected that actual instability had set in before it was possible to hear the burner pulsations. The exit gas temperature was plotted against the square root of dHg across the fuel meter which is proportional to the fuel input. Increasing the fuel causes a rapid rise in temperature up to a certain point although in the lower region the combustion is very rough owing to the very

After a certain point is reached a large increase in fuel is required for a small increase in temperature of exit gases. The points on either side of this point correspond roughly to straight lines. By extrapolating these straight lines to an intersection the lower limit of smooth burning was determined. It is to be noted that the first audible pulsation occurs later than the lower limit determined. The lower limit and the point where pulsation is audible are the lower and upper limits of smooth burning. The average temperature corresponding to the temperature at the center was then taken from the temperature calibration curve.

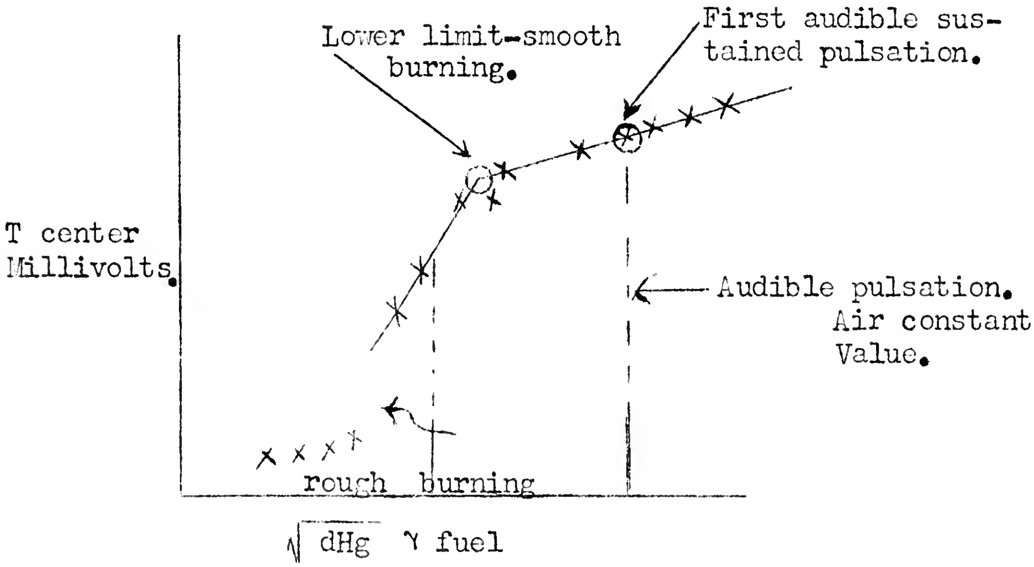



Figure D

## RESULTS AND DISCUSSION

Before any analysis of stability could be attempted, accurate measurement of air and fuel input together with the temperature of the exit gases had to be made. Appendix A-1 shows the details of the fuel meter calibration. It was thought that a temperature calibration curve for each combustion tube would have to be made whereby the average or mean temperature could be read from the maximum temperature of the gases at the center of the tube. Temperature traverses were taken throughout the combustion region with various combustion tubes.

The actual combustion region was about one foot long extending from the flame holder down the tube to the exit. A point 13 1/2" from the flame holder or 1/2" below the end of the combustion tube was selected for the point at which all traverses would be taken. Temperatures were observed to be lower at the exit when longer, or two and one-half foot combustion tubes were used.

Several runs were made on all types of combustion tubes. The details of the combustion tube traverses with the mean temperature evaluated as outlined previously in the procedure are shown in the Appendix B. Fortunately, all the tubes tested fell close to a general curve. Curve 3, Section G, Appendix, shows the results of temperature traverses in plotted form.

The results of the stability test runs are shown in Section C, Appendix. Since in most applications the air supply will be relatively constant and temperature controlled by varying the amount of fuel input, it was decided to conduct the experiment in this manner. The air supply was set on a constant value for the run, and the fuel input increased in increments with the corresponding temperature at the center of the tube recorded. The fuel was increased until continuous sustained pulsation could be heard audibly. The fuel versus temperature curve was plotted and the lower limit of stable burning determined. Curve 2 shows a typical plot of average data. The lower limit was determined as outlined before in the procedure. No audible pulsation was observed on Tube No. 1, 50 mm, pyrex, because flash-back occurred before pulsation indicating definitely that a pressure disturbance existed in the combustion region. Pulsation occurred slightly later in Tube No. 3, 30 mm, pyrex, and it is believed that this was due to the fact that the tube was piped into the system by a rubber connection which in effect shock-mounted the tube. With the tube shock-mounted, the pulsation had to be of greater intensity before it was noted. Table II-C shows a compilation of the results of the stability tests. When the lower limit and audible pulsation points were determined, the average temperature of the exit gases was obtained from the temperature calibration curve, Curve 3.

After the mean temperatures of the exit gases at the lower limit and the audible pulsation points were obtained, the temperature ratios were computed and plotted on a dimensionless plot as shown in Curve 1. Both the lower limit temperature ratio and pulsation temperature ratios are shown plotted on the curve together with the theoretically derived curve previously developed.

Below the lower limit the combustion is rough because the mixture is so lean that it will barely support combustion. Above the audible pulsation point the combustion is obviously unstable. These two points define the region of stable burning. It is suspected that actual instability has begun before it can be heard audibly, and that in the limit these two points should coincide, giving a very narrow band of stable operation.

From Curve 1, it is noted that the variation from the theoretical curve is greater as the temperature ratio increases. This increasing variation can be explained by the fact that no radiation corrections were made to the thermocouple indicated temperatures. If the true temperature is assumed to be on the theoretical curve and the lower point of stability is used:

Radiation Correction $= k\,(T_t)^4$ $\quad T_t$ = Theoretical temp. from curve.

Tube No. 4, 1" pipe, (largest area ratio), requires a radiation loss of 275 degrees for the lower limit point to be on the theoretical curve. Using this value as a basis to compute a common radiation constant, the following values were computed based on the average $T_a$ equal to $69^\circ$ F.

$T_o/T_a$ (Predicated)= $T_o/T_a$ from theoretical curve corrected for radiation loss.

$T_o/T_a$ (Observed)= $T_o/T_a$ from data for lower limit point.

| Radiation Loss Degrees | $T_o/T_a$ (Predicted) | $T_o/T_a$ (Observed) | Error (%) |
|---|---|---|---|
| $275^\circ$ ** | 4.21 | 4.21 | 0 |
| $112^\circ$ | 3.58 | 3.29 | 8.1 |
| $89^\circ$ | 3.34 | 3.19 | 4.5 |
| $47^\circ$ | 2.94 | 2.90 | 1.36 |

**Values used to evaluate radiation constant for all tubes.

Thus, one can observe that by correcting for a radiation loss to bring one of the observed lower limit points to the theoretical curve the other points are brought into corresponding excellent agreement. These limits are well within the experimental error of the experiment. Also the radiation corrections are of the order of magnitude of those to be expected at the corresponding temperatures.

It might further be pointed out that the lower limit of stability for a given area ratio for different values of air flow occurs at the same air to fuel ratio which adds consistency to the results.

The lower limit of stability represents the highest economical temperature ratio of operation since increasing the fuel input beyond this point does not give as great an increase in exit gas temperature. On the other hand, it represents the lowest temperature ratio for stable burning.

The implications are that for a given air supply and flame holder area ratio there is only one point of fuel input for stable burning. Also that control of system by varying fuel input is of little value since an increase or decrease from the lower point of stability will throw the system unstable.

An Orsat analysis on exit gases was conducted on Tube No. 2, 1 1/4" pipe, in order to check the completeness of combustion at the lower limit. Combustion was found to be complete, and the air fuel ratios computed from the Orsat analysis agreed favorably with the computations from air and fuel meters. Section E, Appendix, shows results of the Orsat tests and the calculations.

Table III-C, Appendix, shows the computed air to fuel ratios for both the lower limit of stability point, and point where first audible and continuous pulsation was observed.

Curve 4 is a plot of the mean results. It is interesting to note that throughout the experiment the air to fuel ratios were all greater than that corresponding to stoicheiometric with the exception of one point.

## CONCLUSIONS

Although no final conclusions can definitely be made on the basis of this low flow experiment without further experimentation, the implications are as follows:

(1) The region of stable operation of a flame holder with uniflow, and homogenous mixture of combustible gases is a narrow band on either side of the equation defined by:

$$\frac{A_b}{A_a} = \sqrt{\frac{T_o}{T_a}} - \frac{1}{\sqrt{\frac{T_o}{T_a}}} \quad \ldots\ldots\ldots\ldots \quad (18)$$

Below the temperature ratio corresponding to that defined by equation (18), rough burning is experienced because of the lean mixtures; above this temperature ratio audible pulsation can be heard. Pulsation is believed to start at the lower limit or very soon thereafter, but is not of sufficient intensity to be heard. In the limit the lower limit of stable burning and the initial

pulsation point should approach the same point.

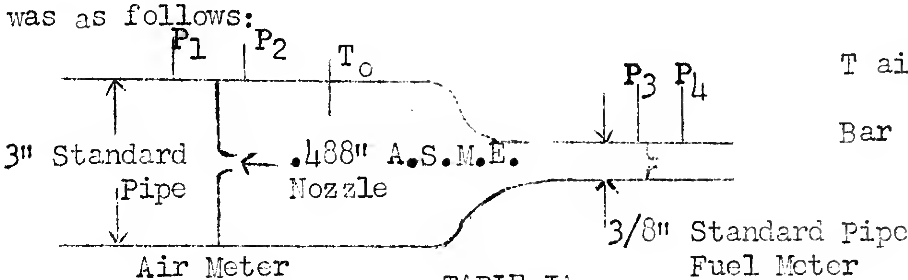
(2) Control of temperature in a combustion tube stabilized by a flame holder with uniflow, homogenous mixture of combustible gases with constant air supply by varying fuel input is not practicable, since smooth burning occurs very nearly at one point. Varying the fuel input either side of this point throws the system into instability.

# A P P E N D I X

# SECTION A

## FUEL METER CALIBRATION

The fuel meter was calibrated with the standard A.S.M.E. .488-inch diameter nozzle. The coefficient of the standard nozzle was assumed to be one. The setup of the calibration was as follows:




T air = 71° F.

Bar = 29.92"Hg.

TABLE IA

FUEL NOZZLE CALIBRATION DATA

| Run | $dH_1$-2 in. $H_2O$ | $P_2$ in. Hg. Gage | $T_o$ - - °F. | $P_3$ in. Hg. Gage | $P_4$ in. $H_2O$ Gage |
|---|---|---|---|---|---|
| 1 | .016 | 2.41 | 66 | 2.41 | 2.2 |
| 2 | .026 | 4.28 | 66 | 4.29 | 3.8 |
| 3 | .036 | 6.55 | 66 | 6.56 | 5.70 |
| 4 | .020 | 3.54 | 66 | 3.54 | 2.70 |
| 5 | .060 | 13.45 | 68 | 13.35 | 10.70 |
| 6 | .068 | 16.20 | 68 | 16.14 | 12.60 |
| 7 | .050 | 10.40 | 68 | 10.40 | 8.3 |
| 8 | .040 | 7.3 | 68 | 7.3 | 6.2 |
| 9 | .030 | 5.3 | 68 | 5.3 | 4.5 |

*The differential head $dH_1$-2 was measured on a one-inch draft gage. The remaining readings were taken on standard U-tube manometers.

Sample calculation:

Since the Mach Number at point 2 is low,

$$\frac{P_1}{P_2} = \left[1 + \frac{\gamma - 1}{2} M_2^2\right]^{\frac{\gamma}{\gamma - 1}} = 1 + \frac{\gamma}{2} M_2^2$$

$$M_2 = \sqrt{\frac{2}{\gamma} \frac{dP}{P_2}} = \sqrt{\frac{d\ H_{1-2}}{P_2}} \sqrt{\frac{2}{\gamma} \times \frac{1}{13.6}} = .325 \sqrt{\frac{d\ H_{1-2}}{P_2}}$$

since,

$$\frac{W \sqrt{T_o}}{PA} = M \sqrt{\frac{\gamma g}{R} \left(1 + \frac{\gamma - 1}{2} M^2\right)} = f\ (M) \quad (4)*$$

$$A_4 \text{ effective} = \frac{P_2}{P_4} \frac{f\ (M_2)}{f\ (M_4)} A_2$$

$$A_2 = 0.187 \text{ sq. in.}$$

$M_4$ was calculated using a reversible expansion from point 3 to point 4. Table II shows a summary of the calculations for $A_4$.

The mean effective area for the nine calibration runs was .00425 sq. in. The drill used to make the nozzle was a number 50 drill of approximately .00384 sq. in. area. The calculated effective area appears to be reasonable allowing for moderate drill whip.

TABLE II-A

SUMMARY OF CALCULATIONS FOR FUEL

NOZZLE CALIBRATION

| Run | $M_2$ | $f(M_2)$* | $M_4$ | $f(M_4)$* | $P_2$" Hg. | $P_4$" Hg. | $A_4$ sq. in. |
|---|---|---|---|---|---|---|---|
| 1 | .00720 | .00660 | .327 | .304 | 32.33 | 30.08 | .00435 |
| 2 | .00934 | .00856 | .435 | .404 | 34.21 | 30.20 | .00451 |
| 3 | .01013 | .00930 | .520 | .489 | 36.51 | 30.34 | .00427 |
| 4 | .00790 | .00725 | .399 | .371 | 33.46 | 30.07 | .00403 |
| 5 | .01200 | .01105 | .720 | .693 | 43.37 | 30.70 | .00426 |
| 6 | .01245 | .01142 | .780 | .757 | 46.12 | 30.85 | .00423 |
| 7 | .01140 | .01046 | .645 | .615 | 40.32 | 30.53 | .00420 |
| 8 | .01060 | .00972 | .567 | .536 | 37.22 | 30.38 | .00416 |
| 9 | .00945 | .00868 | .474 | .448 | 35.22 | 30.26 | .00421 |

$$A_4 \text{ (Effective)} = C_1 A_4 \text{ (Actual)} = \frac{\sum_{n=1}^{n=9} A_n}{9} = .00425 \text{ sq. in.}$$

$$* \; f(M) = M \sqrt{\frac{\gamma g}{R}\left(1 + \frac{\gamma - 1}{2} M^2\right)}$$

SECTION B

TABLE I-B

TEMPERATURE TRAVERSE DATA

Temperatures in Millivolts.
X = distance in inches from center of tube to where temperature was taken.

| X In. | Run 1 50 mm | Run 2 50 mm | Run 3 50 mm | Run 4 35 mm | Run 5 35 mm |
|---|---|---|---|---|---|
| 3/4 | 24.5 | 23.5 | 27.5 | — | — |
| 5/8 | 31.0 | 29.5 | 32.6 | — | — |
| 1/2 | 34.0 | 32.0 | 35.8 | 25.8 | 30.5 |
| 3/8 | 35.3 | 34.2 | 37.5 | 35.7 | 38.7 |
| 1/4 | 36.3 | 35.2 | 38.5 | 40.0 | 42.1 |
| 1/8 | 37.0 | 36.0 | 38.7 | 42.0 | 43.5 |
| 0 | 37.0 | 36.2 | 38.8 | 42.3 | 44.1 |
| 1/8 | 37.0 | 36.0 | 38.7 | 41.9 | 43.6 |
| 1/4 | 36.5 | 35.6 | 38.5 | 40.0 | 41.6 |
| 3/8 | 35.2 | 34.2 | 37.5 | 35.9 | 37.6 |
| 1/2 | 33.5 | 32.7 | 35.5 | 29.5 | 29.5 |
| 5/8 | 30.5 | 28.8 | 31.8 | -- | -- |
| 3/4 | 24.5 | 23.0 | 25.5 | -- | -- |

TABLE I-B (continued)

| X In. | Run 6 35 mm | Run 7 30 mm | Run 8 30 mm | Run 9 30 mm | Run 10 Porcelain |
|---|---|---|---|---|---|
| 1/2 | 30.8 | 28.0 | 33.0 | 37.0 | -- |
| 3/8 | 37.7 | 32.0 | 35.5 | 37.0 | 35.0 |
| 1/4 | 42.0 | 39.5 | 40.5 | 42.0 | 44.7 |
| 1/8 | 44.1 | 42.7 | 44.2 | 45.4 | 46.5 |
| 0 | 44.5 | 43.9 | 45.7 | 46.0 | 47.0 |
| 1/8 | 44.5 | 43.5 | -- | -- | -- |
| 1/4 | 43.2 | 40.5 | -- | -- | -- |
| 3/8 | 39.0 | 33.5 | -- | -- | -- |
| 1/2 | 30.8 | -- | -- | -- | -- |

| X In. | Run 11 Por. | Run 12 Por. | Run 13 1" Pipe | Run 14 1" Pipe | Run 15 1" Pipe |
|---|---|---|---|---|---|
| Wall | 40.0 | 41.2 | 23.6 | 26.0 | 26.5 |
| 3/8 | -- | -- | 31.2 | 35.0 | 36.7 |
| 1/4 | 45.6 | 46.5 | 39.5 | 41.0 | 42.1 |
| 1/8 | 48.4 | 49.5 | 42.4 | 43.8 | 45.0 |
| 0 | 48.6 | 50.0 | 43.6 | 45.1 | 47.0 |
| 1/8 | -- | -- | 41.5 | 44.8 | 46.1 |
| 1/4 | -- | -- | 37.8 | 40.8 | 41.8 |
| 3/8 | -- | -- | 30.5 | 31.0 | 31.8 |
| Wall | -- | -- | 24.8 | 27.5 | 28.1 |

TABLE I-B (continued)

| X In. | Run 16 1 1/4" Pipe | Run 17 1 1/4" Pipe | Run 18 1 1/4" Pipe | Run 19 35 mm | Run 20 30 mm |
|---|---|---|---|---|---|
| Wall | 20.0 | 21.8 | 23.2 | — | — |
| 1/2 | 27.8 | 29.5 | 29.1 | 24.0 | — |
| 3/8 | 32.5 | 34.2 | 30.6 | 30.0 | 24.5 |
| 1/4 | 35.8 | 37.8 | 38.9 | 33.8 | 29.5 |
| 1/8 | 37.5 | 39.5 | 41.0 | 36.7 | 34.5 |
| 0 | 39.0 | 40.5 | 41.8 | 37.4 | 35.5 |
| 1/8 | 38.7 | 40.5 | 41.1 | 36.0 | — |
| 1/4 | 37.5 | 39.8 | 40.2 | 33.2 | — |
| 3/8 | 34.6 | 37.5 | 38.3 | 30.0 | — |
| 1/2 | 28.0 | 32.0 | 32.1 | 24.6 | — |
| Wall | 21.0 | 22.2 | 23.5 | — | — |

| X In. | Run 21 30 mm | Run 22 35 mm | Run 23 25 mm | Run 24 30 mm | Run 25 25 mm | Run 26 50 mm |
|---|---|---|---|---|---|---|
| 3/4 | — | — | — | — | — | 17.2 |
| 5/8 | — | — | — | — | — | 20.5 |
| 1/2 | — | 20.2 | — | — | — | 22.8 |
| 3/8 | 20.0 | 25.0 | 18.0 | 15.5 | 20.0 | 24.0 |
| 1/4 | 25.0 | 27.2 | 20.3 | 19.4 | 21.0 | 24.8 |
| 1/8 | 30.0 | 29.5 | 26.2 | 21.8 | 29.2 | 25.0 |
| 0 | 31.2 | 30.5 | 28.3 | 22.8 | 33.8 | 25.2 |
| 1/8 | 30.9 | 29.0 | 27.4 | 21.4 | 30.5 | — |
| 1/4 | 28.0 | 27.2 | 23.1 | 18.0 | — | — |
| 3/8 | 21.5 | 24.1 | 18.8 | 14.2 | — | — |
| 1/2 | — | 20.5 | — | — | — | — |

TABLE II-B

SUMMARY OF TEMPERATURE TRAVERSE DATA

FOR TEMPERATURE CALIBRATION CURVE

| Run | Tube | T Maximum °F. | T Average °F. |
|---|---|---|---|
| 1 | 50 mm glass | 1635 | 1263 |
| 2 | 50 mm glass | 1600 | 1226 |
| 3 | 50 mm glass | 1715 | 1384 |
| 4 | 35 mm glass | 1880 | 1405 |
| 5 | 35 mm glass | 1965 | 1502 |
| 6 | 35 mm glass | 1990 | 1542 |
| 7 | 30 mm glass | 1955 | 1546 |
| 8 | 30 mm glass | 2040 | 1626 |
| 9 | 30 mm glass | 2055 | 1693 |
| 10 | 1" Porcelain | 2100 | 1795 |
| 11 | 1" Porcelain | 2180 | 1889 |
| 12 | 1" Porcelain | 2250 | 1983 |
| 13 | 1 1/4" steel pipe | 1915 | 1461 |
| 14 | 1 1/4" steel pipe | 2010 | 1511 |
| 15 | 1 1/4" steel pipe | 2095 | 1573 |
| 16 | 1" steel pipe | 1725 | 1288 |
| 17 | 1" steel pipe | 1795 | 1374 |
| 18 | 1" steel pipe | 1835 | 1434 |
| 19 | 35 mm glass | 1640 | 1100 |
| 20 | 30 mm glass | 1570 | 1100 |
| 21 | 30 mm glass | 1380 | 940 |
| 22 | 35 mm glass | 1350 | 935 |
| 23 | 25 mm glass | 1250 | 930 |
| 24 | 30 mm glass | 1020 | 670 |
| 25 | 25 mm glass | 1490 | 1020 |
| 26 | 50 mm glass | 1130 | 770 |

# SECTION C

## TABLE I-C

## STABILITY TEST DATA

| | |
|---|---|
| Pa | Pressure downstream side air nozzle in. Hg. |
| dHa | Pressure differential across air nozzle, in. water. |
| Ta | Temperature of air degrees Fahrenheit. |
| Pg | Pressure downstream side fuel nozzle, in. Hg. |
| dHg | Pressure differential across fuel nozzle, in. water. |
| T | Temperature in millivolts at center of combustion tube. |

**Run 1**

Tube 50 mm Bar 29.92 in. Hg.

| Pa | dHa | Ta |
|---|---|---|
| 5.0 | .50 | 67 |
| **Pg** | **dHg** | **T** |
| 5.4 | .52 | 4.2 |
| 5.7 | .62 | 7.5 |
| 5.8 | .74 | 24.0 |
| 5.8 | .77 | 30.0 |
| 6.1 | .89 | 34.8 |
| 6.35 | 1.00 | 36.5 |
| 6.75 | 1.15 | 37.6 |
| 7.25 | 1.30 | 38.0 |
| 7.25 | 1.32 | 39.3 |
| 7.5 | 1.43 | 40.1 |
| 7.7 | 1.47 | 41.0 |

**Run 2**

Tube 50 mm Bar 30.20 in. Hg.

| Pa | dHg | Ta |
|---|---|---|
| 4.1 | .50 | 66 |
| **Pg** | **dHg** | **T** |
| 5.2 | .75 | 32.5 |
| 4.6 | .56 | 15.8 |
| 4.6 | .50 | 9.0 |
| 5.0 | .66 | 23.0 |
| 5.2 | .79 | 33.5 |
| 5.6 | .92 | 35.5 |
| 5.9 | 1.04 | 36.2 |
| 6.1 | 1.16 | 37.8 |
| 6.2 | 1.24 | 38.2 |
| 6.4 | 1.26 | 38.0 |
| 6.7 | 1.40 | 39.2 |

**Run 3**

Tube 50 mm Bar 29.92 in. Hg.

| Pa | dHa | Ta |
|---|---|---|
| 6.5 | .80 | 67 |
| **Pg** | **dHg** | **T** |
| 5.15 | .87 | 3.5 |
| 9.7 | 1.15 | 15.5 |
| 10.3 | 1.35 | 32.0 |
| 10.8 | 1.55 | 37.0 |
| 11.0 | 1.78 | 40.5 |
| 11.4 | 1.97 | 41.8 |
| 11.7 | 2.14 | 42.0 |
| 12.5 | 2.47 | 43.6 |
| 12.6 | 2.52 | 43.6 |

**Run 4**

Tube 50 mm Bar 30.20 in. Hg.

| Pa | dHa | Ta |
|---|---|---|
| 7.8 | .80 | 66 |
| **Pg** | **dHg** | **T** |
| 9.5 | 1.06 | 5.0 |
| 9.6 | 1.18 | 17.2 |
| 9.7 | 1.23 | 29.2 |
| 9.7 | 1.20 | 28.5 |
| 9.9 | 1.35 | 33.8 |
| 10.1 | 1.40 | 35.0 |
| 10.1 | 1.47 | 35.6 |
| 10.2 | 1.51 | 36.5 |
| 10.25 | 1.61 | 37.0 |
| 10.8 | 1.85 | 38.2 |
| 11.0 | 1.97 | 39.2 |
| 11.8 | 2.25 | 41.0 |
| -- | 2.70 | 44.0 |

TABLE I-C (continued)

| Run 5 | | |
|---|---|---|
| 1 1/4" Pipe | Bar 29.92 in. Hg. | |
| Pg | dHa | Ta |
| 4.1 | .50 | 66 |
| Pg | dHg | T |
| 5.1 | .50 | 4.5 |
| 5.7 | .72 | 15.5 |
| 5.8 | .96 | 37.1 |
| 6.35 | 1.14 | 40.0 |
| 7.0 | 1.33 | 41.2 |
| 7.2 | 1.43 | 42.5** |
| 7.5 | 1.48 | 43.0 |
| 7.9 | 1.63 | 43.5 |
| 8.3 | 1.85 | 44.5 |
| 8.5 | 1.97 | 46.0 |
| 9.1 | 2.20 | 48.0 |
| 9.7 | 2.45 | 49.0 |

| Run 6 | | |
|---|---|---|
| 1 1/4" Pipe | Bar 29.92 in. Hg. | |
| Pa | dHa | Ta |
| 4.1 | .50 | 66 |
| Pg | dHg | T |
| 5.5 | .70 | 11.8 |
| 5.7 | .72 | 19.5 |
| 5.9 | .80 | 33.0 |
| 6.3 | 1.00 | 38.8 |
| 6.5 | 1.20 | 40.9 |
| 7.1 | 1.43 | 42.5** |

| Run 7 | | |
|---|---|---|
| 1 1/4" Pipe | Bar 29.92 in. Hg. | |
| Pa | dHa | Ta |
| 8.5 | .80 | 70 |
| Pg | dHg | T |
| 9.2 | .75 | 8.5 |
| 10.1 | 1.26 | 22.5 |
| 10.8 | 1.50 | 38.8 |
| 10.9 | 1.57 | 39.0 |
| 10.35 | 1.37 | 33.0 |
| 11.25 | 1.77 | 41.0 |
| 11.4 | 1.99 | 42.3 |
| 12.3 | 2.22 | 43.5** |

| Run 8 | | |
|---|---|---|
| 1" Pipe | Bar 29.92 in. Hg. | |
| Pa | dHa | Ta |
| 5.1 | .50 | 71 |
| Pg | dHg | T |
| 7.0 | 1.38 | 41.0 |
| 7.5 | 1.66 | 47.5 |
| 7.9 | 1.90 | 49.0 |
| 9.2 | 2.34 | 51.0 |
| 8.4 | 1.96 | 49.5 |
| 9.1 | 2.21 | 51.0** |
| 10.1 | 2.61 | 52.0 |

| Run 9 | | |
|---|---|---|
| 1" Pipe | Bar 29.92 in. Hg. | |
| Pa | dHa | Ta |
| 5.8 | .70 | 72 |
| Pg | dHg | T |
| 9.0 | 1.86 | 42.0 |
| 9.9 | 2.14 | 49.2 |
| 10.3 | 2.49 | 50.5 |
| 11.3 | 2.88 | 52.0** |

| Run 10 | | |
|---|---|---|
| 1" Pipe | Bar 30.20 in. Hg. | |
| Pa | dHa | Ta |
| 4.8 | .50 | 66 |
| Pg | dHg | T |
| 7.8 | 1.63 | 44.5 |
| 8.2 | 1.77 | 47.3 |
| 8.6 | 2.01 | 48.8 |
| 9.3 | 2.20 | 49.5 |
| 9.9 | 2.36 | 50.0** |
| 10.4 | 2.67 | 51.2 |
| 10.8 | 2.82 | 51.5 |
| 10.0 | 2.50 | 50.5 |

**Point where first audible continuous pulsation observed.

TABLE I-C (continued)

| Run 11 | | |
|---|---|---|
| 1" Pipe | Bar 30.20 in. Hg. | |
| Pa | dHa | Ta |
| 4.8 | .50 | 66 |
| Pg | dHg | T |
| 8.2 | 1.63 | 41.0 |
| 8.3 | 1.76 | 44.0 |
| 8.4 | 1.80 | 45.5 |
| 8.9 | 1.98 | 48.2 |
| 9.4 | 2.24 | 49.5 |
| 10.1 | 2.50 | 50.5** |
| 11.1 | 2.95 | 53.0 |

| Run 12 | | |
|---|---|---|
| 1 1/4" Pipe | Bar 30.20 in. Hg. | |
| Pa | dHa | Ta |
| 4.6 | .50 | 69 |
| Pg | dHg | T |
| 5.6 | .72 | 16.5 |
| 5.6 | .73 | 19.5 |
| 5.9 | .90 | 33.5 |
| 6.2 | 1.03 | 36.7 |
| 6.6 | 1.23 | 38.9 |
| 6.9 | 1.34 | 40.0 |
| 7.4 | 1.50 | 41.2** |
| 7.7 | 1.69 | 42.1 |
| 8.0 | 1.84 | 43.1 |
| 8.4 | 2.00 | 44.7 |
| 9.2 | 2.36 | 45.7 |
| 10.1 | 2.67 | 47.0 |

| Run 13 | | |
|---|---|---|
| 1 1/4" Pipe | Bar 30.35 in Hg. | |
| Pa | dHa | Ta |
| 4.9 | .50 | 68 |
| Pg | dHg | T |
| 5.8 | .56 | 10.5 |
| 6.0 | .68 | 20.5 |
| 6.1 | .74 | 31.2 |
| 6.1 | .76 | 35.5 |
| 6.8 | .94 | 38.2 |
| 7.2 | 1.07 | 39.0 |
| 7.8 | 1.30 | 41.2 |
| 8.8 | 1.60 | 43.0** |
| 9.2 | 1.74 | 44.0 |
| 10.9 | 2.30 | 47.0 |

| Run 14 | | |
|---|---|---|
| 1 1/4" Pipe | Bar 30.35 in. Hg. | |
| Pa | dHa | Ta |
| 4.9 | .50 | 68 |
| Pg | dHg | T |
| 6.1 | .63 | 21.0 |
| 6.5 | .75 | 33.6 |
| 6.8 | .90 | 37.2 |
| 7.2 | 1.00 | 38.6 |
| 7.4 | 1.22 | 40.8 |
| 8.0 | 1.36 | 41.8 |
| 8.6 | 1.53 | 42.8** |
| 9.0 | 1.76 | 44.5 |
| 10.0 | 2.05 | 45.5 |
| 10.9 | 2.25 | 46.5 |

**Point where first audible continuous pulsation observed.

TABLE I-C (continued)

| Run 15 | | |
|---|---|---|
| 1 1/4" Pipe | Bar 30.35 | in. Hg. |
| Pa | dHg | Ta |
| 9.0 | .80 | 68 |
| 11.1 | 1.33 | 36.2 |
| 10.6 | 1.16 | 31.2 |
| 12.0 | 1.55 | 39.0 |
| 12.3 | 1.67 | 39.8 |
| 12.6 | 1.82 | 41.2 |
| 13.2 | 2.05 | 42.2** |
| 14.0 | 2.25 | 43.2 |
| 14.6 | 2.42 | 44.0 |
| 15.2 | 2.63 | 45.2 |
| 16.2 | 2.98 | 46.2 |

| Run 16 | | |
|---|---|---|
| 1 1/4" Pipe | Bar 30.35 | in. Hg. |
| Pa | dHg | Ta |
| 9.0 | .80 | 68 |
| 11.0 | 1.25 | 33.4 |
| 11.4 | 1.40 | 38.2 |
| 11.6 | 1.55 | 39.5 |
| 12.0 | 1.65 | 40.1 |
| 12.7 | 1.78 | 41.1 |
| 13.2 | 2.07 | 43.0** |
| 13.6 | 2.20 | 43.2 |
| 14.4 | 2.38 | 44.1 |
| 14.8 | 2.54 | 44.8 |
| 15.2 | 2.66 | 45.2 |
| 15.8 | 2.85 | 46.1 |
| 16.4 | 3.03 | 46.2 |

| Run 17 | | |
|---|---|---|
| 1" Pipe | Bar 30.35. | in. Hg. |
| Pa | dHg | Ta |
| 5.0 | .50 | 68 |
| Pg | dHg | T |
| 8.2 | 1.82. | 42.0 |
| 8.2 | 1.86 | 43.1 |
| 8.9 | 1.96 | 44.5 |
| 9.3 | 2.14 | 45.5 |
| 10.0 | 2.37 | 46.5 |
| 10.25 | 2.56 | 47.5 |
| -- | 2.60 | 47.2 |
| 11.2 | 2.96 | 49.5 |

| Run 18 | | |
|---|---|---|
| 1" Pipe | Bar 30.35 | in. Hg. |
| Pa | dHa | Ta |
| 5.0 | .50 | 70 |
| Pg | dHg | T |
| 9.1 | 1.69 | 43.8 |
| 9.5 | 1.79 | 44.6 |
| 10.0 | 1.92 | 45.8 |
| 10.5 | 2.07 | 46.8 |
| 11.3 | 2.28 | 47.5 |
| 12.2 | 2.57 | 49.5 |
| 13.2 | 2.84 | 51.0 |

**Point where first audible continuous pulsation observed.

TABLE I-C (continued)

| Run 19 | | |
|---|---|---|
| 35 mm Tube | Bar 30.35 | in Hg. |
| Pa | dHg | Ta |
| 4.8 | .50 | 70 |
| Pg | dHg | T |
| 6.2 | .81 | 23.1 |
| 6.7 | .92 | 36.1 |
| 6.8 | .96 | 37.8 |
| 7.0 | 1.12 | 39.2 |
| 7.2 | 1.20 | 40.0 |
| 7.4 | 1.30 | 41.0 |
| 8.0 | 1.50 | 42.1 |
| 7.8 | 1.35 | 41.0 |
| 8.7 | 1.75 | 44.0 |
| 9.0 | 1.89 | 44.5 |
| 9.5 | 2.08 | 44.0 |
| 10.9 | 2.55 | 46.0** |

| Run 20 | | |
|---|---|---|
| Tube 35 mm | Bar 30.35 | in. Hg. |
| Pa | dHa | Ta |
| 4.8 | .50 | 70 |
| Pg | dHg | T |
| 6.0 | .70 | 26.5 |
| 6.2 | .78 | 30.3 |
| 6.4 | .86 | 35.2 |
| 6.5 | .97 | 37.5 |
| 6.8 | 1.07 | 38.8 |
| 7.2 | 1.20 | 40.2 |
| 7.5 | 1.24 | 40.5 |
| 7.8 | 1.33 | 41.2 |
| 8.0 | 1.57 | 42.3 |
| 8.5 | 1.67 | 43.3 |
| 8.9 | 1.83 | 44.5 |
| 9.2 | 1.95 | 45.5 |
| 9.9 | 2.17 | 46.0** |
| 10.3 | 2.36 | 46.2 |
| 11.0 | 2.55 | 47.0 |

| Run 21 | | |
|---|---|---|
| 35 mm Tube | Bar 30.35 | in. Hg. |
| Pa | dHa | Ta |
| 8.1 | .80 | 70 |
| Pg | dHg | T |
| 10.6 | 1.33 | 28.5 |
| 11.3 | 1.56 | 38.7 |
| 11.8 | 1.66 | 40.0 |
| 12.3 | 1.92 | 41.5 |
| 12.6 | 2.03 | 42.6 |
| 13.0 | 2.15 | 42.8 |
| 13.2 | 2.24 | 43.0 |
| 14.0 | 2.43 | 44.0 |
| 14.2 | 2.66 | 45.1 |
| 15.0 | 2.88 | 46.0** |
| 17.8 | 3.00 | 45.0 |

| Run 22 | | |
|---|---|---|
| Tube 35 mm | Bar 30.35 | in. Hg. |
| Pa | dHa | Ta |
| 8.1 | .80 | 70 |
| Pg | dHg | T |
| 10.6 | 1.26 | 29.5 |
| 11.0 | 1.42 | 36.0 |
| 11.4 | 1.64 | 39.2 |
| 11.9 | 1.77 | 40.5 |
| 12.3 | 1.98 | 42.0 |
| 12.7 | 2.09 | 42.1 |
| 12.7 | 2.24 | 43.0 |
| 14.2 | 2.60 | 45.0 |
| 14.7 | 2.78 | 45.5 |
| 15.2 | 2.92 | 46.2** |

**Point where first audible continuous pulsation observed.

TABLE II-C

RESULTS OF STABILITY TESTS

Tc' Lower limit of stability temperature in millivolts at center of combustion tube.
Tc" Temperature in °F. corresponding to Tc'.
To Average temperature obtained from Curve 3.
To/Ta Temperature ratio.
Tp Temperature in millivolts corresponding to first sustained audible pulsation.

| Run | Tube | Tc' | Tc" | To | To/Ta | Tp |
|---|---|---|---|---|---|---|
| 1 | 50 mm | 33.5 | 1480 | 1030 | 2.82 | -- |
| 2 | 50 mm | 34.5 | 1525 | 1075 | 2.89 | -- |
| 3 | 50 mm | 35.0 | 1545 | 1090 | 2.94 | -- |
| 4 | 50 mm | 35.0 | 1545 | 1090 | 2.94 | -- |
| 5 | 1 1/4"pipe | 37.7 | 1670 | 1230 | 3.20 | 42.5 |
| 6 | 1 1/4"pipe | 37.5 | 1660 | 1215 | 3.17 | 42.5 |
| 7 | 1 1/4"pipe | 38.0 | 1680 | 1245 | 3.23 | 43.5 |
| 8 | 1" pipe | 47.0 | 2100 | 1785 | 4.26 | 51.0 |
| 9 | 1" pipe | 48.0 | 2150 | 1850 | 4.38 | 52.0 |
| 10 | 1" pipe | 47.2 | 2110 | 1800 | 4.28 | 50.0 |
| 11 | 1" pipe | 47.2 | 2110 | 1800 | 4.28 | 50.5 |
| 12 | 1 1/4"pipe | 37.0 | 1635 | 1190 | 3.12 | 41.2 |
| 13 | 1 1/4"pipe | 36.7 | 1622 | 1185 | 3.11 | 43.0 |
| 14 | 1 1/4"pipe | 36.7 | 1622 | 1185 | 3.11 | 42.8 |
| 15 | 1 1/4"pipe | 38.0 | 1680 | 1240 | 3.22 | 42.2 |
| 16 | 1 1/4"pipe | 38.2 | 1690 | 1255 | 3.24 | 43.0 |
| 17 | 1" pipe | 45.5 | 2055 | 1695 | 4.06 | -- |
| 18 | 1" pipe | 45.5 | 2055 | 1695 | 4.06 | -- |
| 19 | 35 mm | 39.5 | 1750 | 1325 | 3.38 | 46.0 |
| 20 | 35 mm | 39.4 | 1745 | 1320 | 3.37 | 46.0 |
| 21 | 35 mm | 39.7 | 1760 | 1335 | 3.39 | 46.0 |
| 22 | 35 mm | 39.5 | 1750 | 1325 | 3.38 | 46.2 |

MEAN RESULTS

| | To/Ta(Lower Limit) | Tp/Ta(Pulsation) |
|---|---|---|
| Tube No. 1; 50 mm | 2.88 | -- |
| Tube No. 2; 1 1/4"pipe | 3.19 | 3.75 |
| Tube No. 3; 35 mm | 3.39 | 4.15 |
| Tube No. 4, 1" pipe | 4.20 | 4.73 |

TABLE III-C

AIR TO FUEL RATIO FOR STABILITY TESTS

| Run | Lower Limit-Air to Fuel Ratio | Audible Pulsation-Air To Fuel Ratio |
|---|---|---|
| 1 | 27.7 | -- |
| 2 | 28.1 | -- |
| 3 | 26.5 | -- |
| 4 | 27.0 | -- |
| 5 | 26.2 | 20.1 |
| 6 | 26.7 | 20.1 |
| 7 | 26.0 | 20.6 |
| 8 | 20.1 | 16.2 |
| 9 | 20.5 | 16.4 |
| 10 | 18.4 | 15.6 |
| 11 | 18.15 | 15.0 |
| 12 | 25.8 | 19.9 |
| 13 | 28.0 | -- |
| 14 | 27.8 | 18.7 |
| 15 | 26.1 | 21.3 |
| 16 | 26.1 | 21.2 |
| 17 | 17.45 | -- |
| 18 | 17.5 | -- |
| 19 | 25.4 | 14.7 |
| 20 | 25.4 | 16.1 |
| 21 | 24.5 | 18.0 |
| 22 | 25.1 | 17.3 |

MEAN VALUES OF AIR TO FUEL RATIO

| | | |
|---|---|---|
| Tube No. 1 | 27.3 | -- |
| Tube No. 2 | 26.6 | 20.3 |
| Tube No. 3 | 25.1 | 16.5 |
| Tube No. 4 | 18.7 | 15.8 |

**Stoichiometric composition for combustion of propane corresponds to an air to fuel ratio of 15.8.

# SECTION D

## AIR AND FUEL FLOW CALCULATIONS

Air Measurement:

$\gamma$ Ratio of specific heats, 1.395 for air.

k Slope of the f(M) flow curve for very low Mach Numbers, .918.

A Air nozzle area, .187 sq. in.

Pa Pressure at downstream side of air nozzle in in. Hg.

dHa Differential pressure across the air nozzle in in. water.

$$\frac{Po}{Pa} = \left[1 + \frac{\gamma-1}{2} M^2\right]^{\frac{\gamma}{\gamma-1}} = 1 + \frac{\gamma M^2}{2} \cdot \cdot \cdot$$

$$\frac{Po - Pa}{Pa} = \frac{dHa}{Pa} = \frac{\gamma M^2}{2} \quad \text{for low Mach Numbers } M < .1$$

$$Ma = \sqrt{\frac{2}{\gamma} \frac{dHa}{Pa}}$$

$$\frac{W\sqrt{To}}{PA} = M\sqrt{\frac{\gamma g}{R}\left(1 + \frac{\gamma-1}{2} M^2\right)} = K\ (M) \quad \text{for low Mach Numbers}$$

$$W = .491 \times .918 \times .187 \sqrt{\frac{2}{r} \frac{1}{13.6}} \sqrt{\frac{Pa\ dHa}{Ta}}$$

$$W = .0274\sqrt{\frac{Pa\ dHa}{Ta}} \quad \text{lb. air/sec.}$$

Fuel Measurement:

r Ratio of specific heats of propane, 1.153

k Slope of the f(M) flow curve for very low Mach numbers for propane, 1.0295.

A Area of the fuel nozzle by calibration, .00425 sq. in.

Pg Pressure on the downstream side of the fuel nozzle in in. Hg.

dHg Differential across the fuel nozzle in in. water. Using the binominal expansion for low Mach Numbers as in air measurement.

$$Mg = \sqrt{\frac{2}{r}\ \frac{dHg}{Pg}} = \sqrt{\frac{2}{r}\ \frac{1}{13.6}\frac{dH_g}{P_g}} = .355\ \sqrt{\frac{dHg}{Pg}}$$

but,

$$\frac{w\sqrt{To}}{PA} = M\sqrt{\frac{rg}{R}\left(1 + \frac{r-1}{2}M^2\right)} = KMg = 1.0295\ Mg$$

$$w = .491 \times 1.0295 \times .355 \times .00425\sqrt{\frac{Pg\ dHg}{Tg}} =$$

$$.000764\sqrt{\frac{Pg\ dHg}{Tg}}\ \text{lb./sec. propane}$$

# SECTION E

## ORSAT ANALYSIS

DATA:

| | | | |
|---|---|---|---|
| Pa | 5.1 in Hg. Gage | Pg | 6.5 in Hg. gage |
| dHa | .51 in $H_2O$ | dHg | .95 in $H_2O$ |
| ta | 66° F. | To | 36 millivolts |
| Combustion tube 1 1/4" pipe | | Bar | 29.77 in Hg. |

Orsat Analysis Results:

| | Run 1 | Run 2 | Average |
|---|---|---|---|
| $CO_2$ | 6.8% | 7.5% | 7.15% |
| $O_2$ | 9.0% | 9.8% | 9.4% |
| CO | Neg. | Neg. | Neg. |
| $N_2$ | 84.2% | 82.7% | 83.45% |

Calculations:

Basis 100 moles of dry gas.

Carbon = 7.15 x 44 x 12/44 = 85.6 lbs.

Weight Propane = 85.6 x 44/36 = 105 lbs. propane for 100 moles dry gases.

Weight Air = 83.45 x 28/77 = 3030 lbs. air for 100 moles dry gases.

Air/Fuel Ratio from Orsat = 3030/105 = 28.8

Air/Fuel Ratio, Run 2 = 27.3

From Air and Fuel Meters:

Weight Air = $.0274 \sqrt{\frac{Pa\ dHa}{Ta}}$ = .00502 lbs. air/sec.

Weight Fuel = $.000764 \sqrt{\frac{Pg\ dHg}{Tg}}$ = .000195 lbs. fuel/sec.

Air/Fuel Ratio from Meters = .00502/.000195 = 25.8

Calculations of Carbon to Hydrogen Ratio:

Weight of Carbon = 85.6 lbs.

Weight of $O_2$ = 3030 x .23 = 696 lbs.

Weight of $O_2$ Excess = 9.4 x 32 = 301 lbs.

Weight of $O_2$ in $CO_2$ = 7.15 x 32 = 229 lbs.

wt $O_2$ in $H_2O$ = 696 - (301+299) = 166 lbs.

wt. of H. in fuel = 166 x 2/16 = 20.7

C/H ratio observed = $\dfrac{\frac{85.6}{12}}{20.7/1} = \dfrac{7.14}{20.7} = \dfrac{2.76}{8}$

C/H ratio of fuel, propane = 3/8

# SECTION F

## SYMBOLS

$A$ = Flow area, sq. ft.

$dH$ = Differential drop across meter in in. of water.

$g$ = Acceleration of gravity, 32.2 ft. per sec. per sec.

$M$ = Mach number.

$P$ = Absolute pressure, lbs. per sq. ft.

$\gamma$ = Ratio of specific heats.

$R$ = Gas constant, 53.3 in. lbs. ft. per $^{o}R$.

$T$ = Static temperatures $^{o}R$.

$T_o$ = Total temperature $^{o}R$.

$V$ = Velocity, ft. per second.

$W$ = Flow, lbs. per second.

$\rho$ = Mass density slugs per cu. ft.

$d$ = Total derivative

$\delta$ = Partial derivative

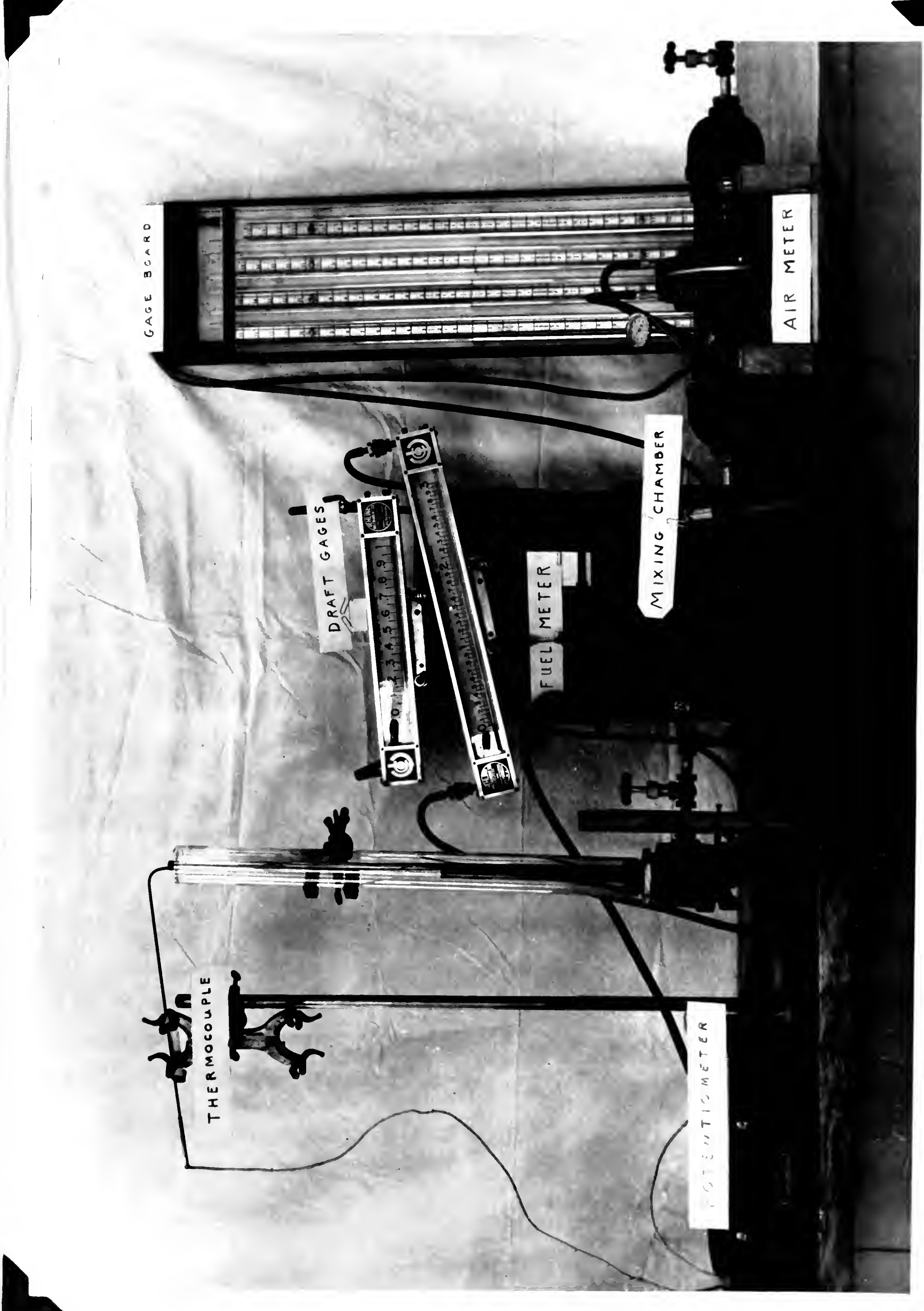
Subscripts are used throughout paper for designation of point properties, and where they are used their significance is explained.

# SECTION G

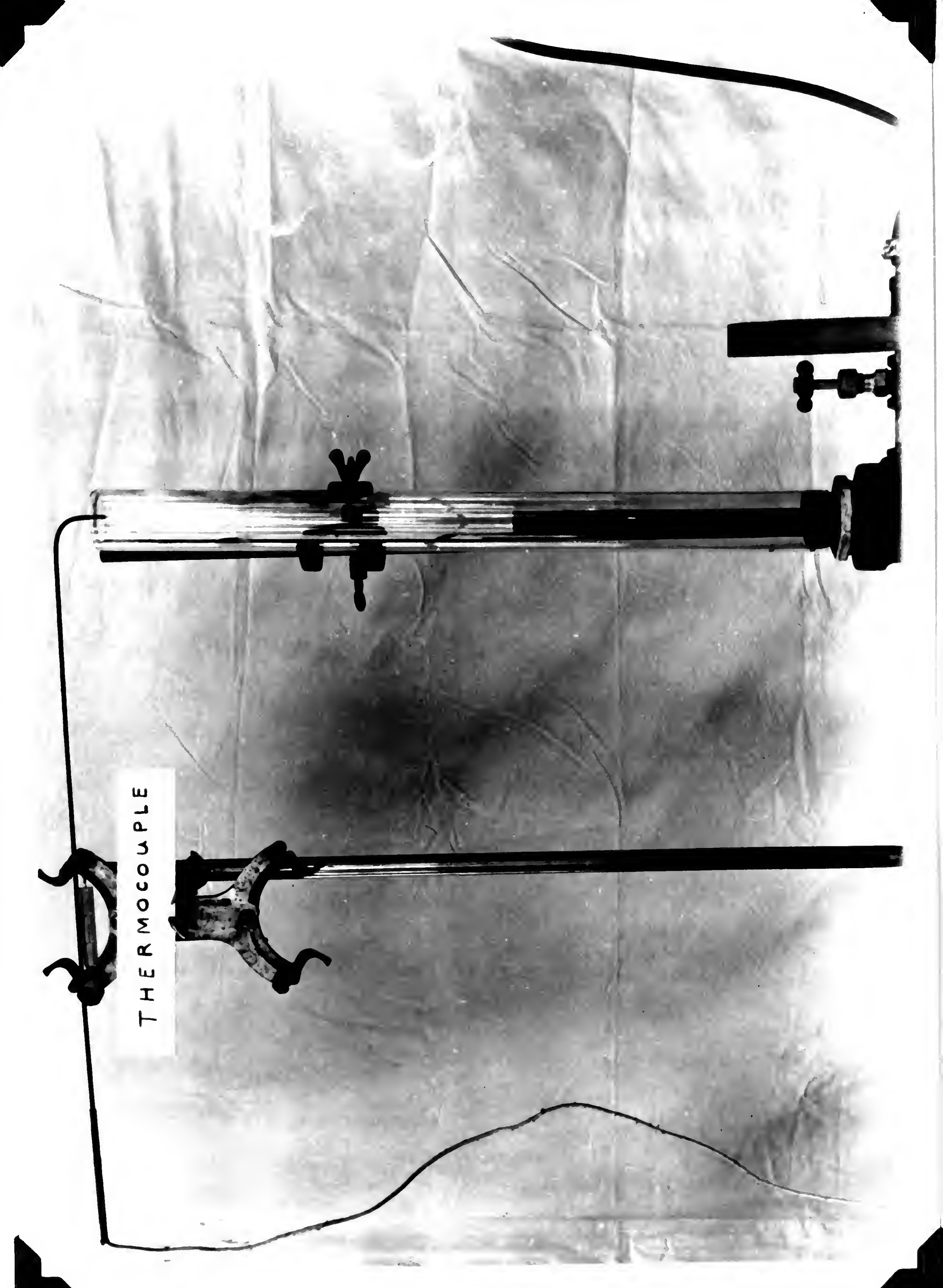
## PHOTOGRAPHS

Photograph 1 - The experimental apparatus.

Photograph 2 - Details of combustion tube.




PHOTOGRAPH 1 - THE EXPERIMENTAL APPARATUS




PHOTOGRAPH 2 - DETAILS OF THE COMBUSTION TUBE

# SECTION H

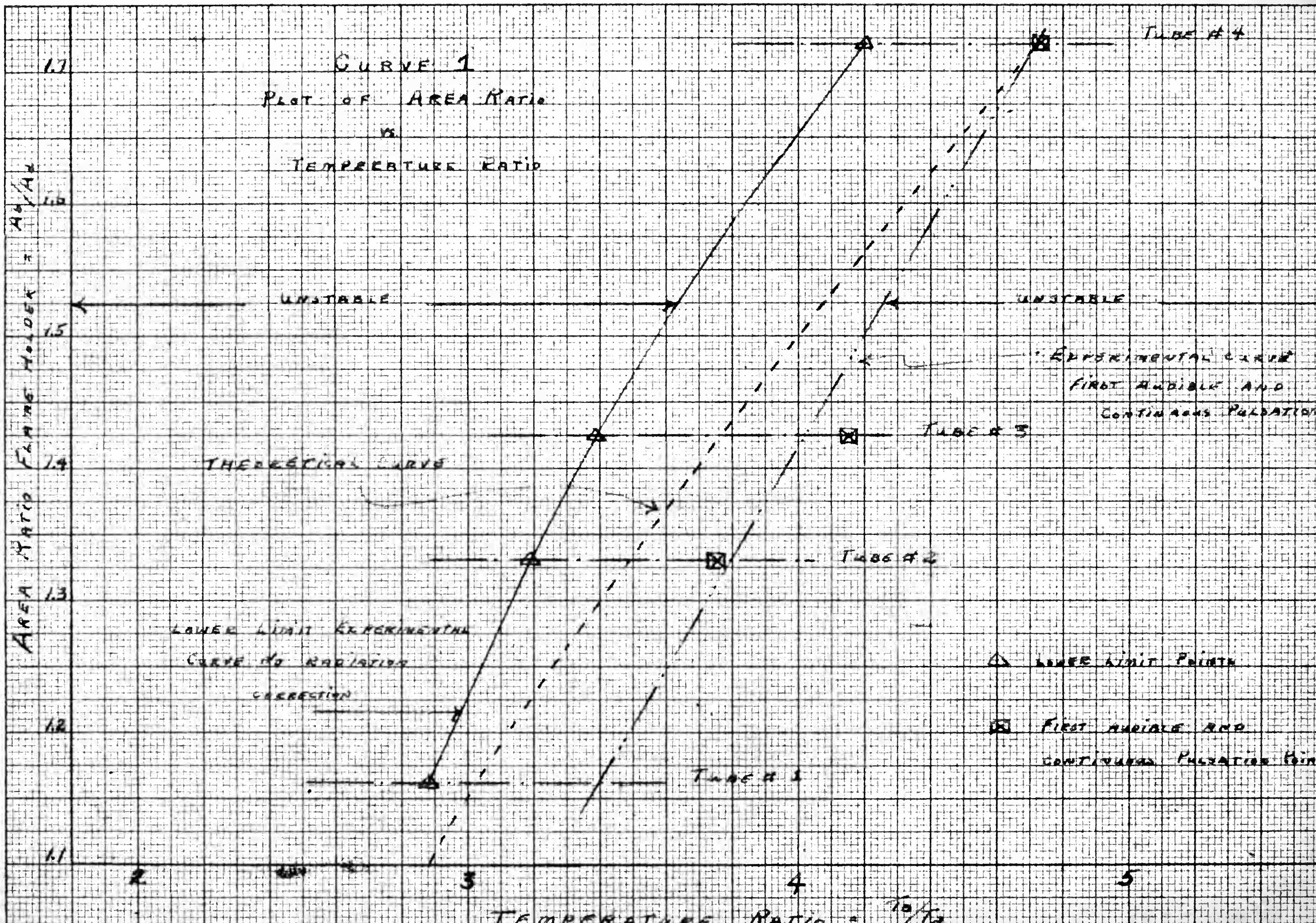
## CURVES

Curve 1 - Plot of area ratio versus temperature ratio.

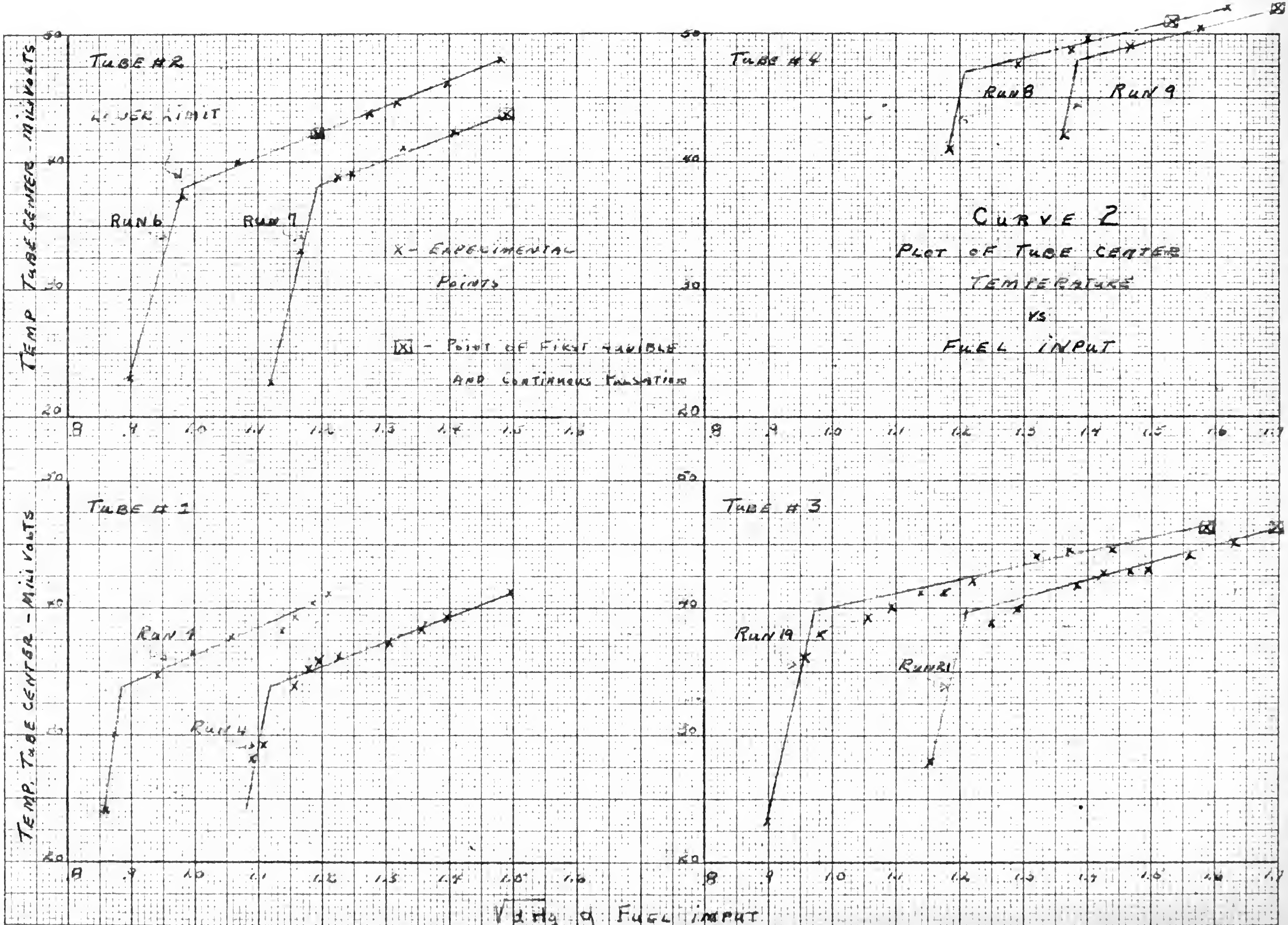
Curve 2 - Plot of tube center temperature versus fuel input.

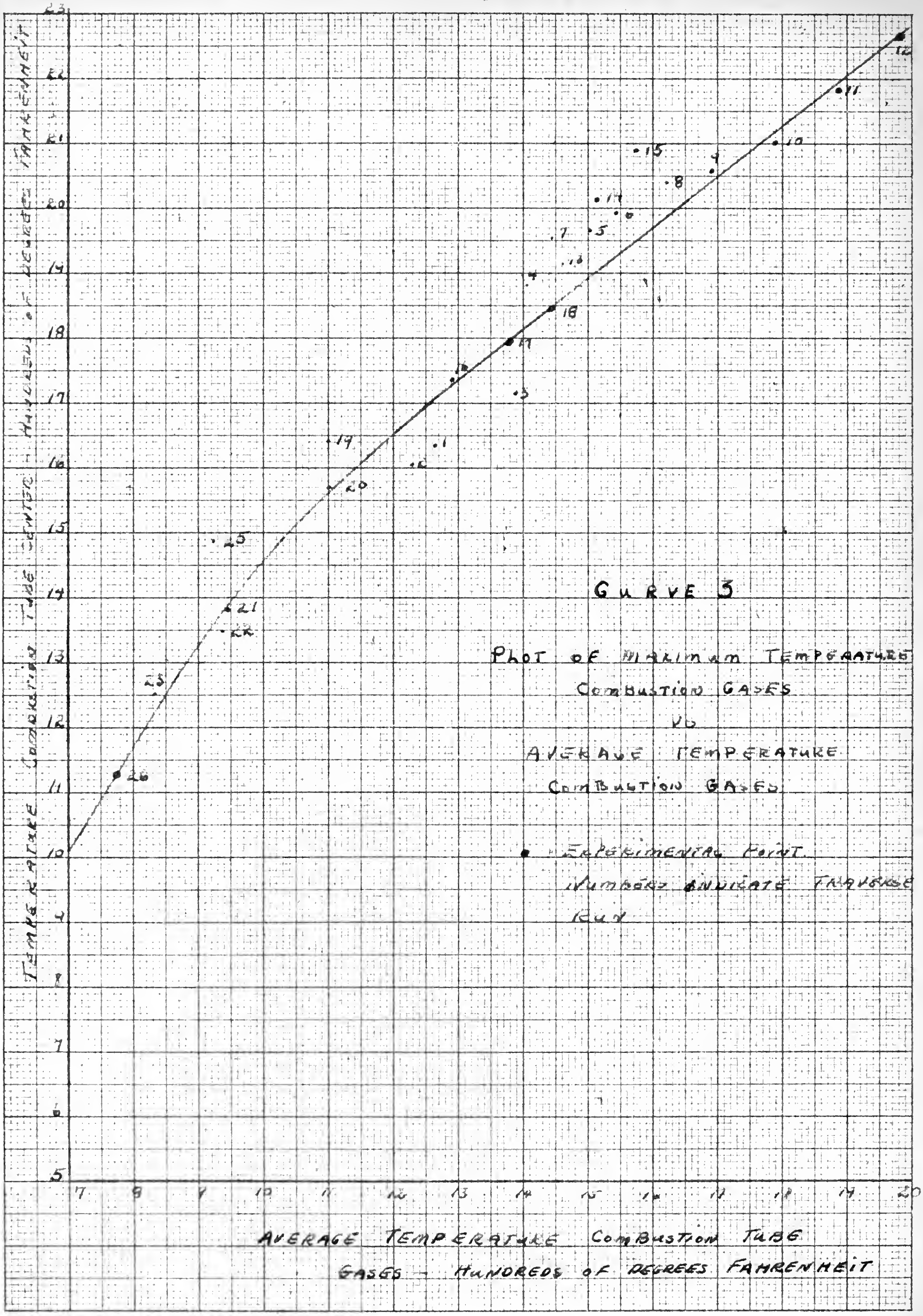
Curve 3 - Plot of maximum temperature of combustion gases versus average temperature of combustion gases.

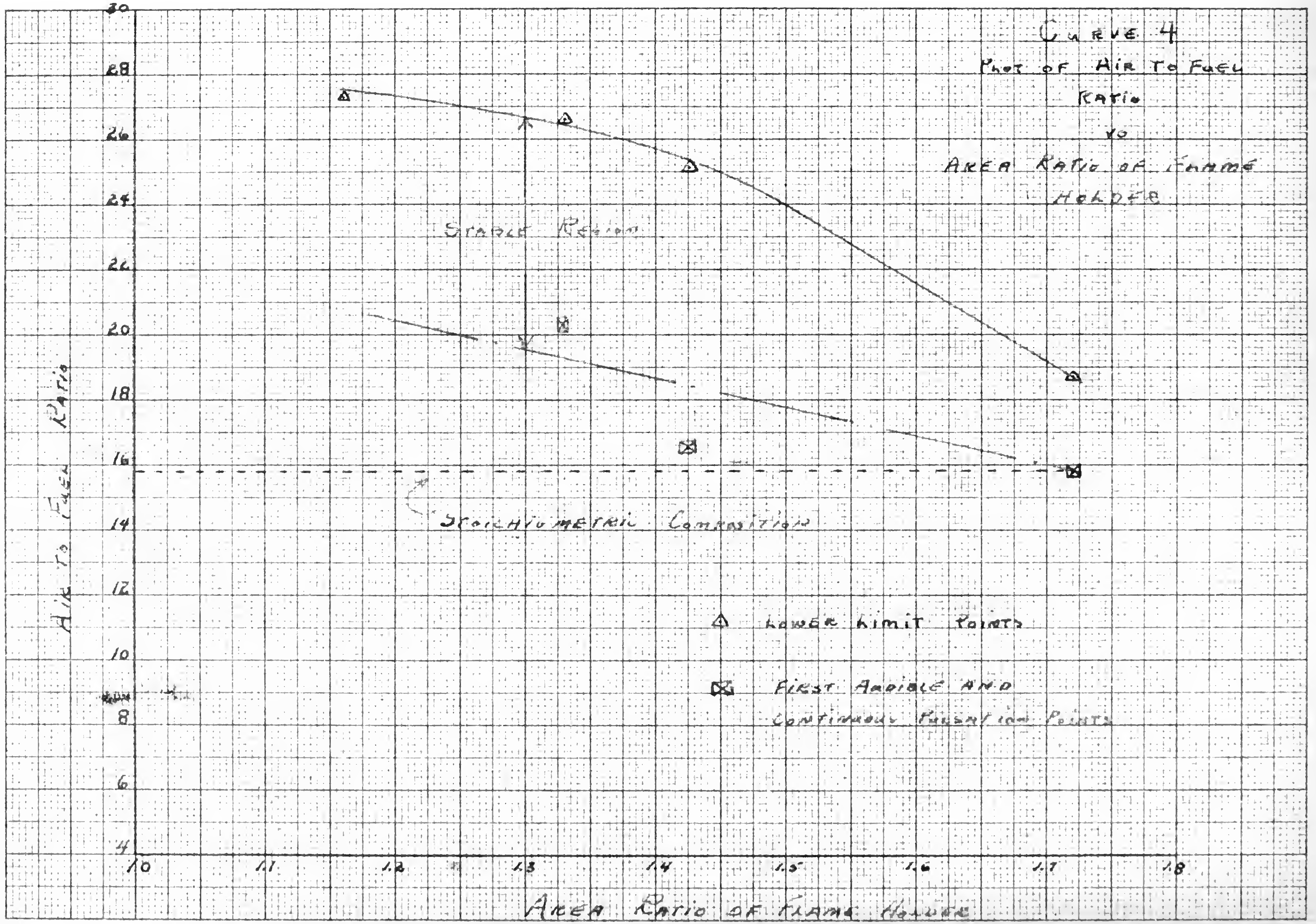
Curve 4 - Plot of air to fuel ratio versus area ratio of flame holder.



CURVE 1
PLOT OF AREA RATIO
vs
TEMPERATURE RATIO
UNSTABLE
UNSTABLE
EXPERIMENTAL CURVE
FIRST AUDIBLE AND
CONTINUOUS PULSATION
TUBE # 4
TUBE # 3
TUBE # 2
TUBE # 1
THEORETICAL CURVE
LOWER LIMIT EXPERIMENTAL
CURVE NO RADIATION
CORRECTION
LOWER LIMIT POINTS
FIRST AUDIBLE AND
CONTINUOUS PULSATION POINTS
AREA RATIO FLAME HOLDER = $A_0/A_d$
TEMPERATURE RATIO = $T_0/T_d$
1.1
1.2
1.3
1.4
1.5
1.6
1.7
2
3
4
5


Curve 2
Plot of Tube Center Temperature vs Fuel Input
X - Experimental Points
[X] - Point of First Audible and Continuous Pulsation
Tube #2
Lower Limit
Run 6
Run 7
Tube #4
Run 8
Run 9
Tube #1
Run 4
Run 4
Tube #3
Run 19
Run 21
Temp Tube Center - Milivolts
Temp. Tube Center - Milivolts
√"Hg of Fuel Input


CURVE 3
PLOT OF MAXIMUM TEMPERATURE
COMBUSTION GASES
VS
AVERAGE TEMPERATURE
COMBUSTION GASES
• EXPERIMENTAL POINT
NUMBERS INDICATE TRAVERSE
RUN
TEMPERATURE COMBUSTION TUBE CENTER - HUNDREDS OF DEGREES FAHRENHEIT
AVERAGE TEMPERATURE COMBUSTION TUBE
GASES - HUNDREDS OF DEGREES FAHRENHEIT



Curve 4
Plot of Air to Fuel Ratio vs Area Ratio of Flame Holder
Stable Region
Stoichiometric Composition
Lower Limit Points
First Audible and Continuous Pulsation Points
Air to Fuel Ratio
Area Ratio of Flame Holder
30
28
26
24
22
20
18
16
14
12
10
8
6
4
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8

# SECTION I

## BIBLIOGRAPHY

(1)* "Flame Propagation, Critical Review of Existing Theories", by George H. Markstein and Michael L. Polanyi. Non-classified Bumblebee Series Report No. 61, June 1947, prepared for Bureau of Ordnance, U. S. Navy.

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